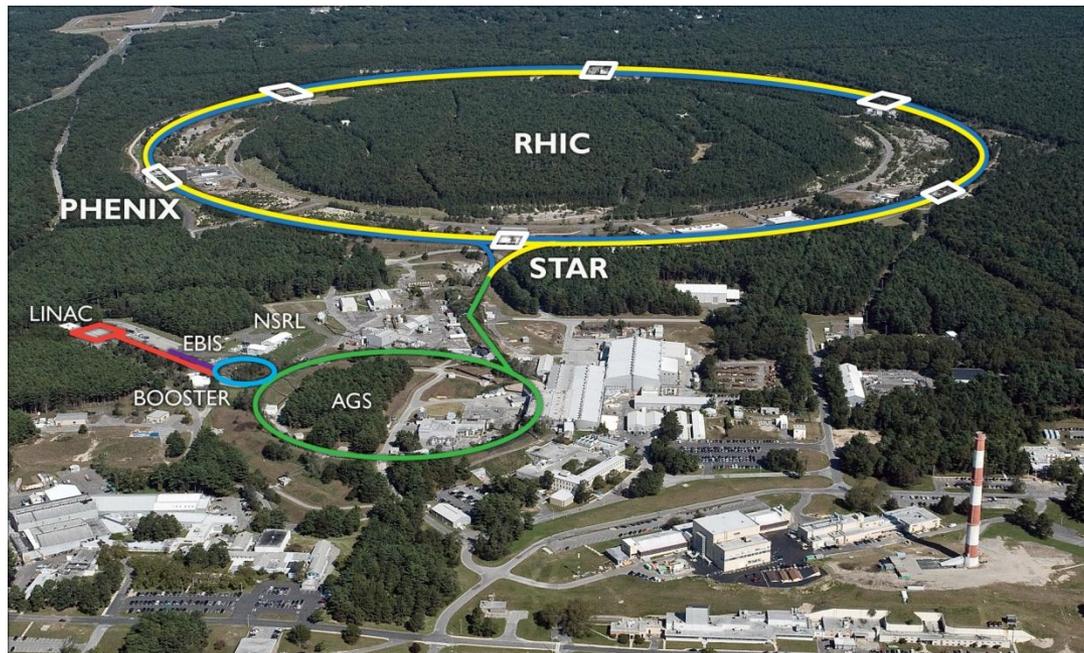


# Open heavy flavor measurements at RHIC



**Mustafa Mustafa**

Purdue University

2013 RHIC & AGS Annual Users' Meeting

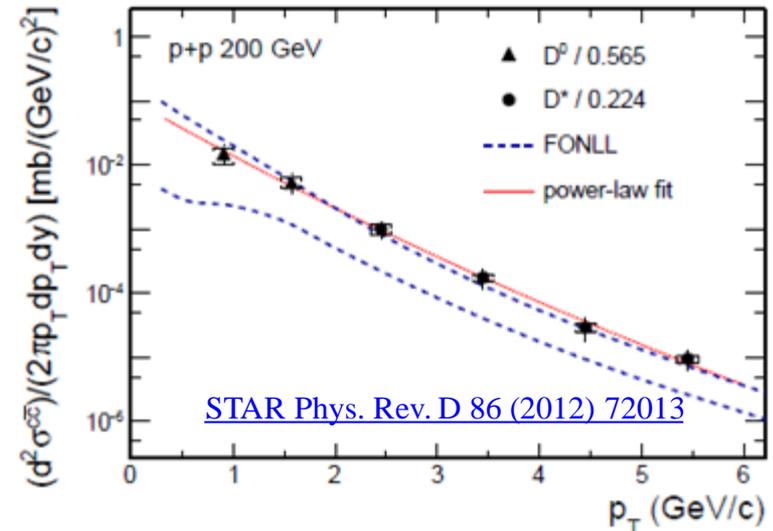
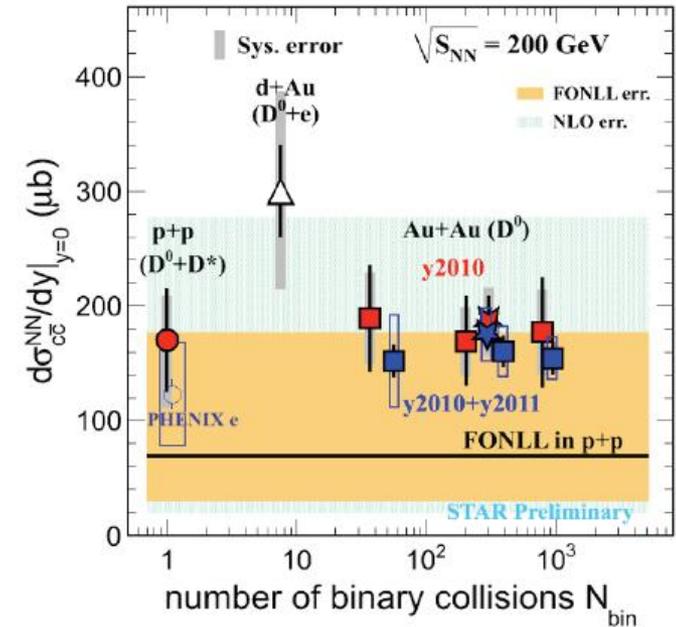
**PURDUE**  
UNIVERSITY

## Introduction

- Why heavy flavor?
- Experimental observables.
  - The big picture.

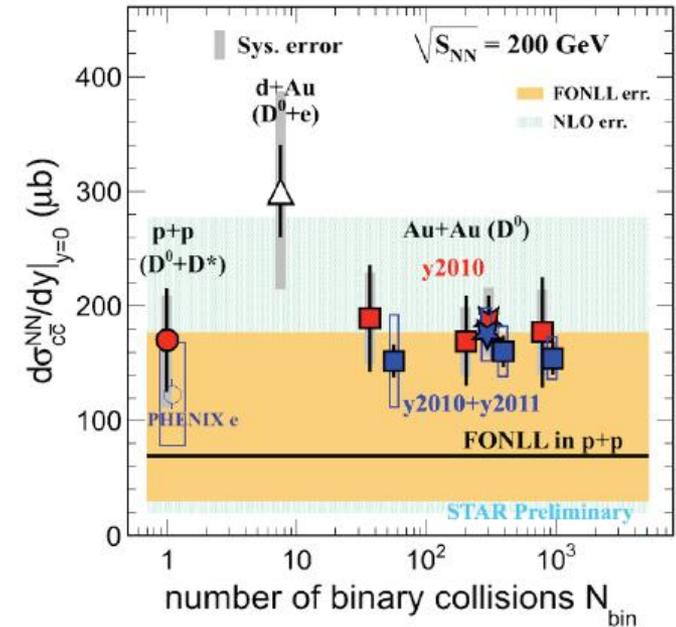
# Why Heavy Flavor?

- Due to their large masses, heavy quarks are created at the early stage of HIC through initial hard scattering, thus:
  - pQCD cross-sections, power-law at high  $p_T$ .
  - cross-sections scale by  $N_{bin}$ .
  - experience all stages of medium evolution.
- Their masses are external to QCD.

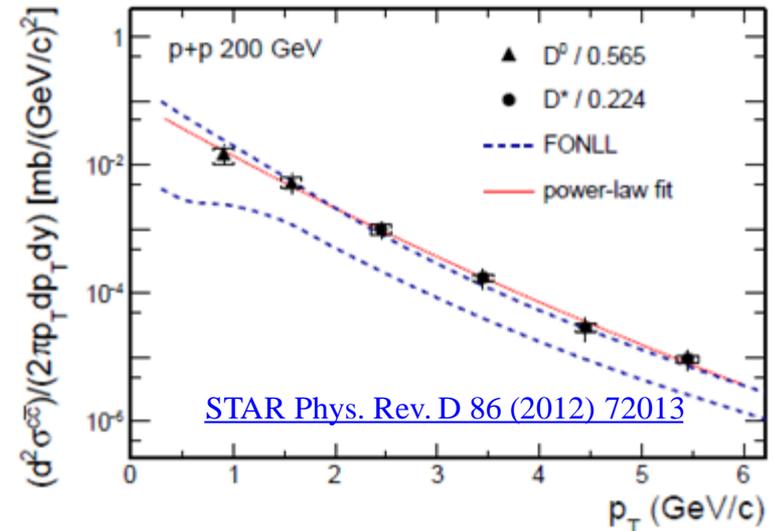


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Heavy Quarks are clean probes to study the bulk matter created in heavy-ion collisions.



# Heavy Quarks as probes of sQGP

Heavy Quarks experience all the stages of medium evolution

→ their kinematics carry information about their interaction with the medium.

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## Observables:

- Modification of the power-law  $\mathbf{p}_T$  spectra (high  $\mathbf{p}_T$ )
  - Study flavor dependence of partons energy loss.  
(gluon density,  $\hat{q}$ , drag and diffusion coefficients).

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- Azimuthal Anisotropy
  - Low  $\mathbf{p}_T$   $v_2$  ( $< 2\text{GeV}/c$ )
    - Charm flow → degree of thermalization of the bulk matter.
    - Important to understand Quarkonia production mechanisms in HIC.

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  - High  $\mathbf{p}_T$   $v_2$ 
    - path length dependence of energy loss.  
(an important differential measurement to test parton energy loss models, LPM, near  $T_c$  enhancement, AdS/CFT).

# Reconstructing Open Heavy Flavor

- Direct reconstruction through hadronic decay channels

- ✓ Allows direct access to the heavy quark kinematics.

- Hard to trigger.

- Limit the  $p_T$  reach .

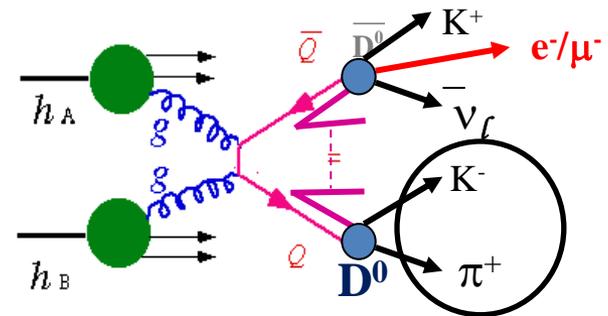
- Small(er) Branching Ratio:

- $B^+ \rightarrow K^+ + J/\psi \rightarrow ee$ :  $BR: \sim 6 \times 10^{-5}$

- $B^0 \rightarrow K\pi$ :  $BR: \sim 5 \times 10^{-6}$

- $D^0 \rightarrow K\pi$ :  $BR: \sim 4\%$

- $D^+ \rightarrow K\pi\pi$ :  $BR: \sim 9.4\%$  (lower acceptance)



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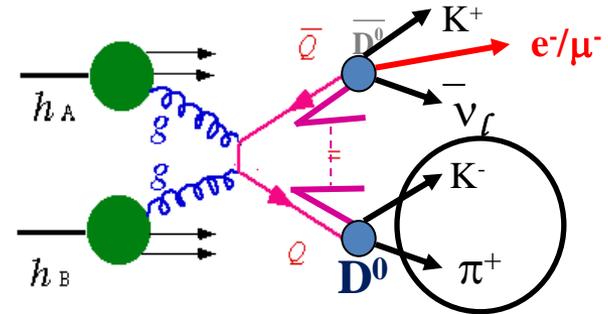
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## ○ Indirect measurement through semi-leptonic decay channels

• Indirect access to the heavy quark kinematics

✓ Can be triggered easily.

• Ideal for high  $p_T$  measurements

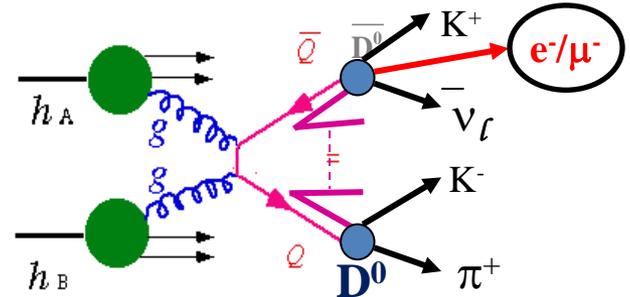
✓ High(er) branching ratio

•  $B \rightarrow e^+ + X$ :  $BR: \sim 10\%$

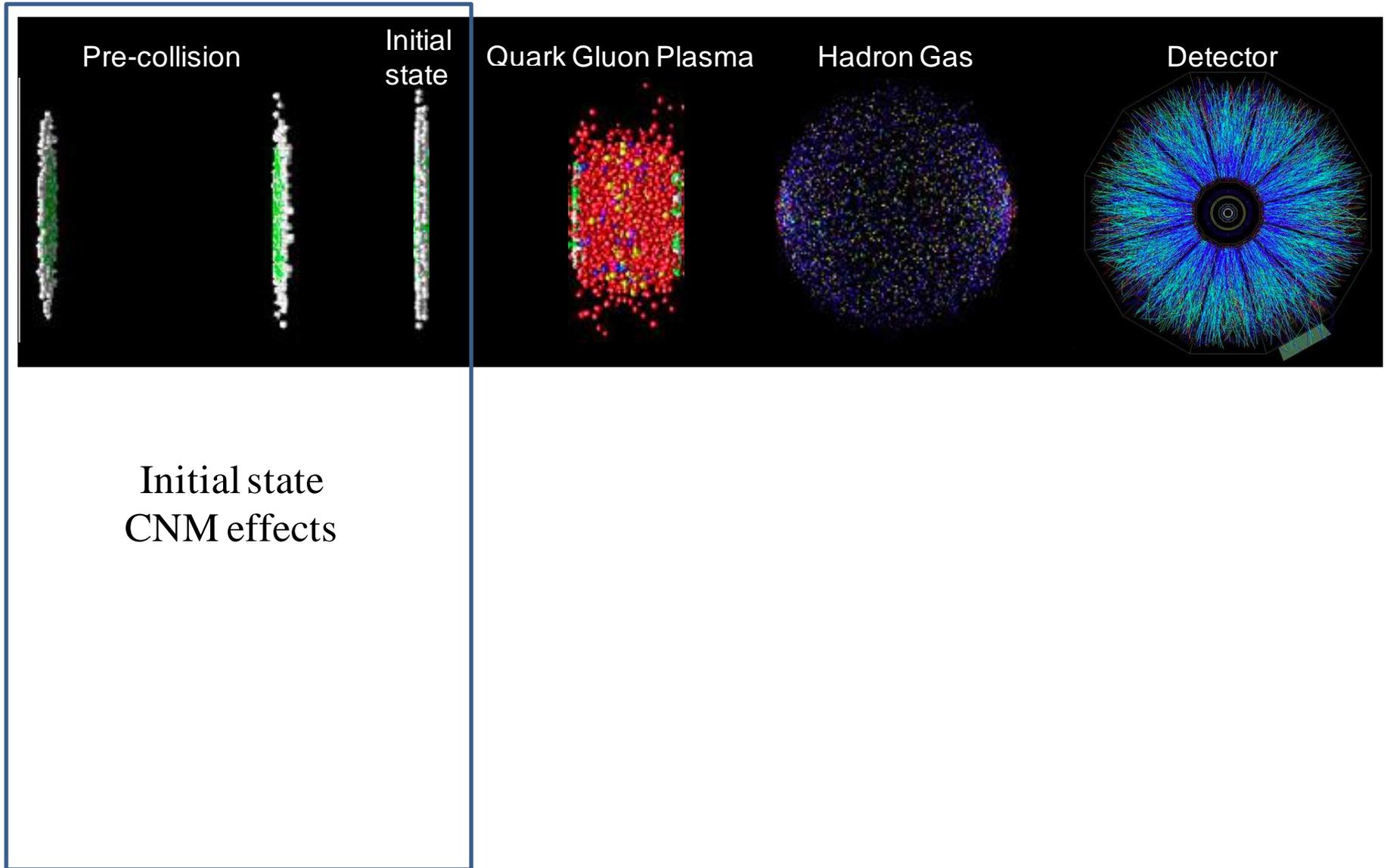
•  $D^0 \rightarrow e^+ + X$ :  $BR: \sim 6.5\%$

•  $D^+ \rightarrow e^+ + X$ :  $BR: \sim 16\%$

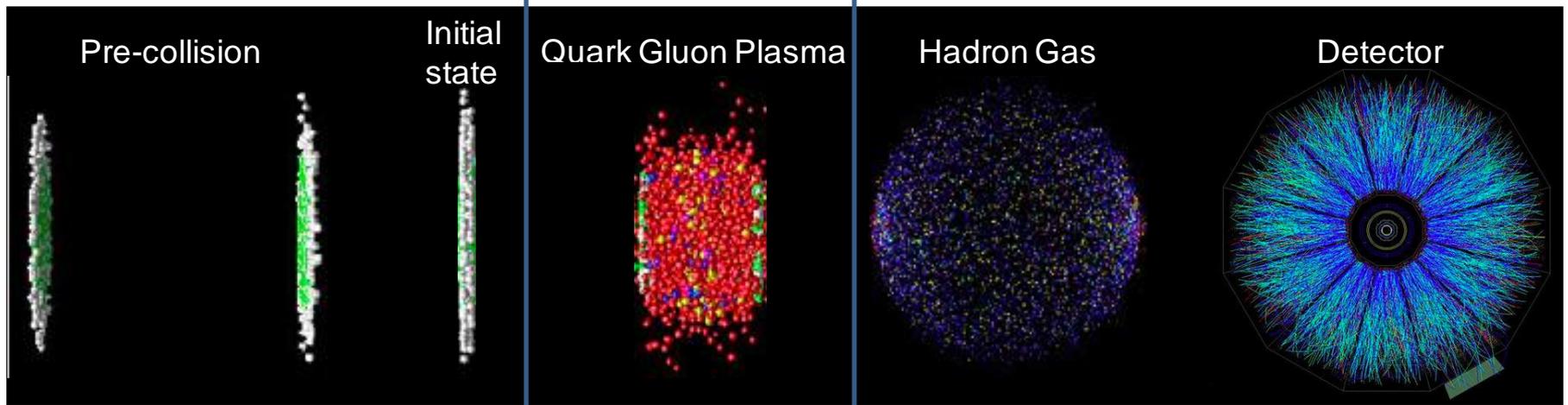
•  $\Lambda_c \rightarrow e^+ + X$ :  $BR: \sim 4.5\%$  (Lightest charmed baryon)



# The big picture



# The big picture



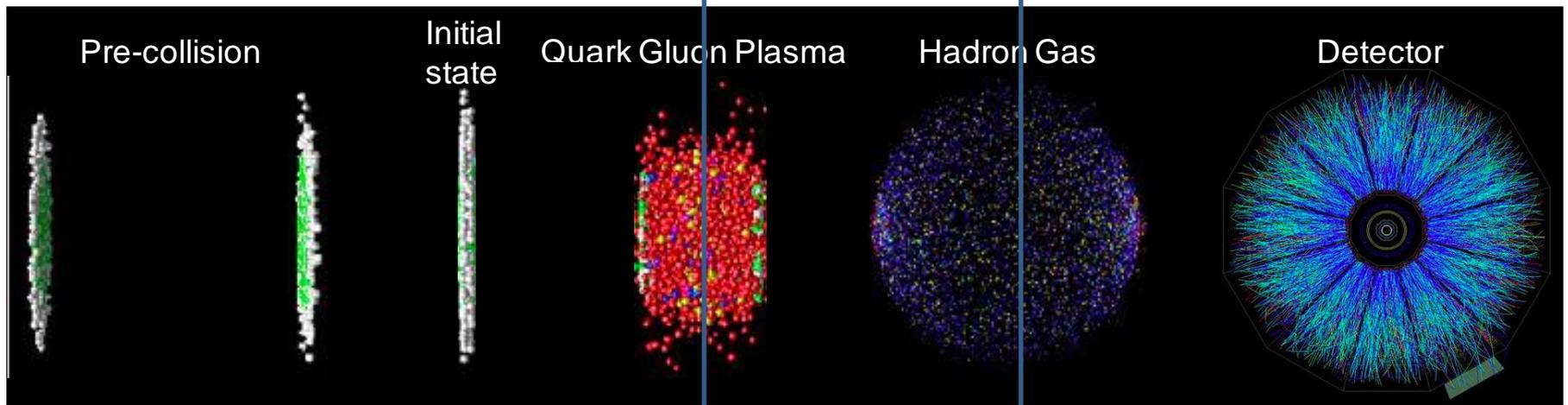
## HQ med. Inter.

- pQCD: rad. , col. & col. dissoc.
- non-pQCD: resonance scattering
- AdS/CFT.

## Med. Evol.

- hydro.
- transport.

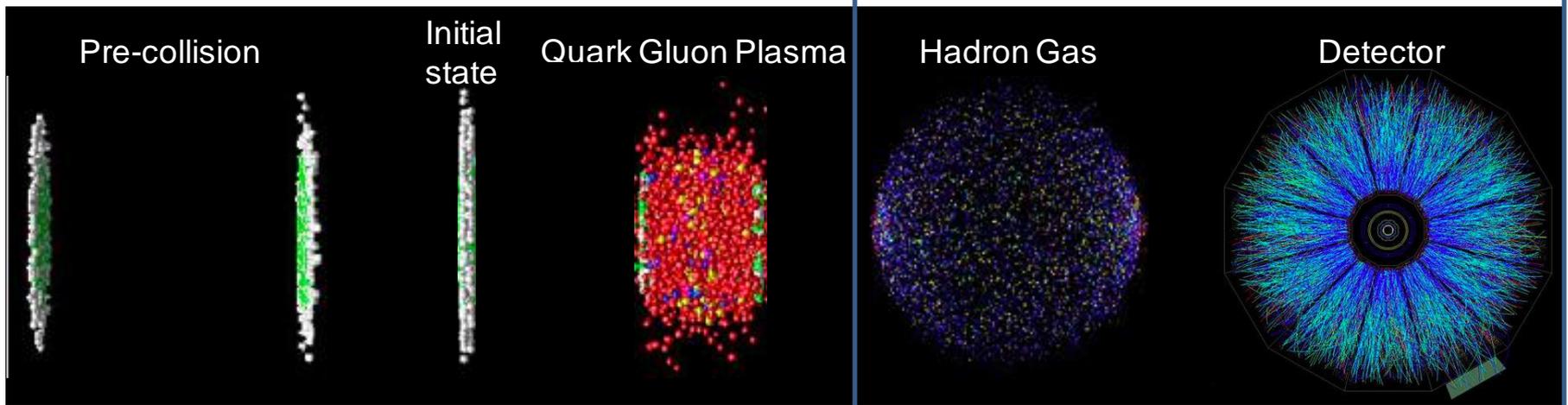
# The big picture



## Hadronization:

- coalescence.
- fragmentation.
- med. modified fragmentation.

# The big picture

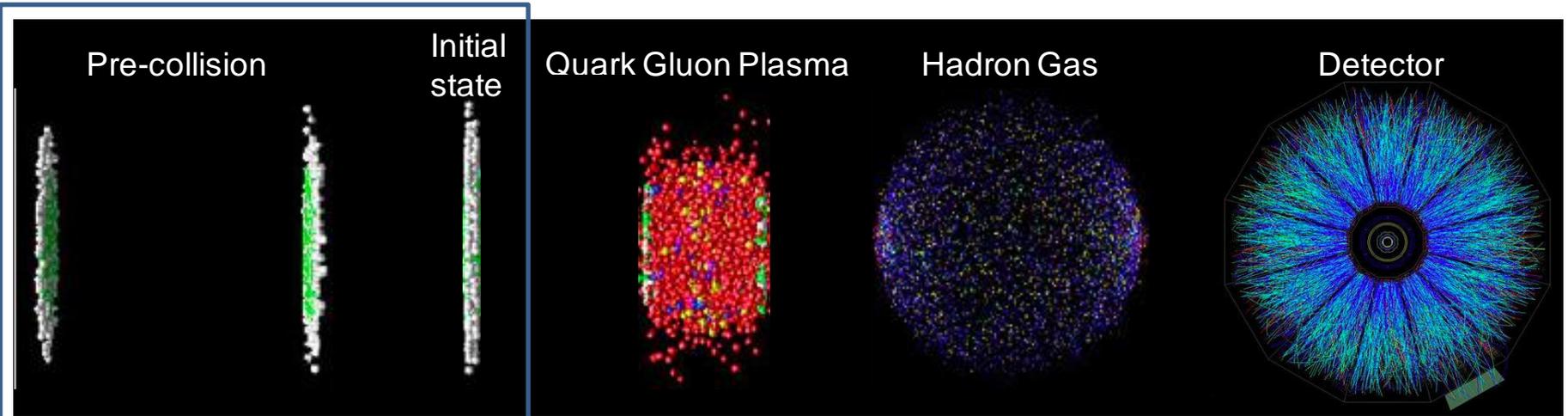


Hadronic rescattering .

then free streaming and decay.

finally, measurement and analysis.

# Measurements



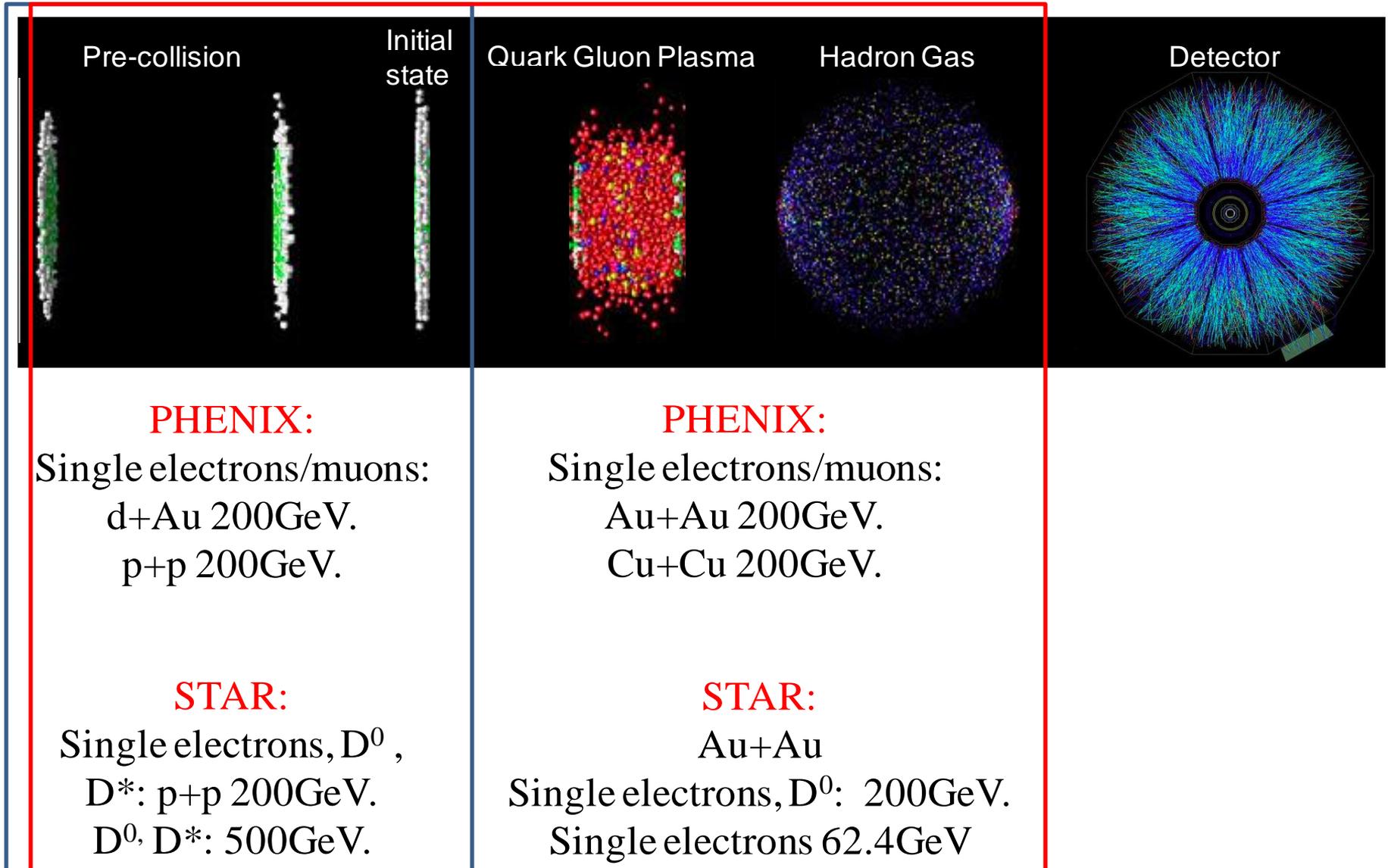
## PHENIX:

Single electrons/muons:  
d+Au 200GeV.  
p+p 200GeV.

## STAR:

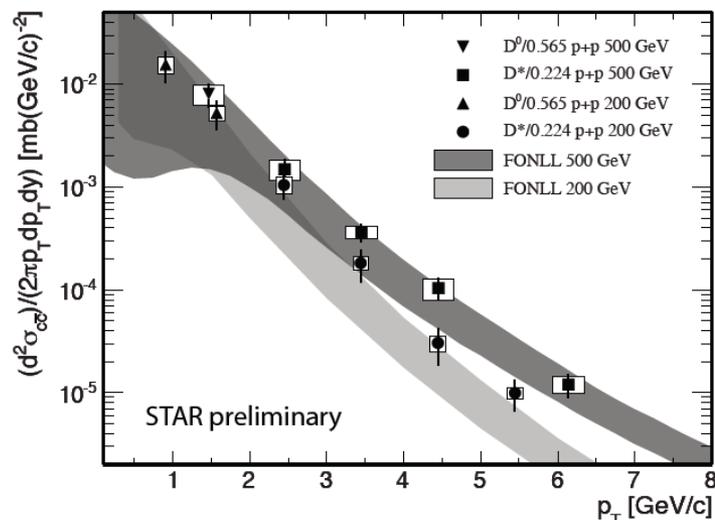
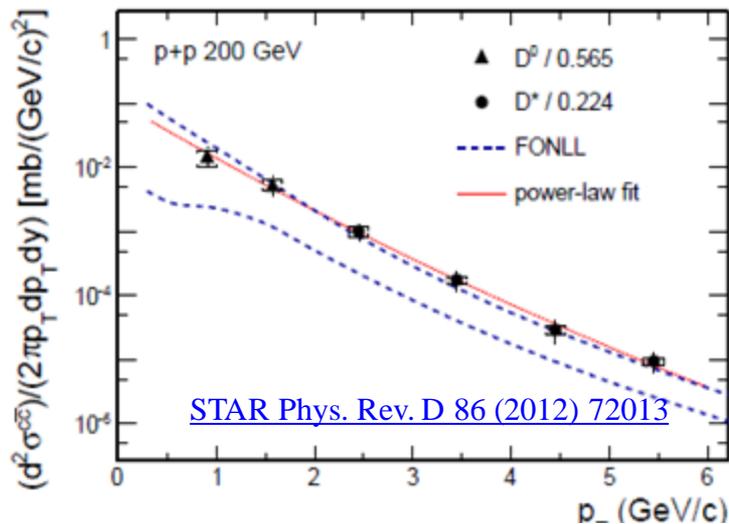
Single electrons,  $D^0$ ,  
 $D^*$ : p+p 200GeV.  
 $D^0$ ,  $D^*$ : 500GeV.

# Measurements

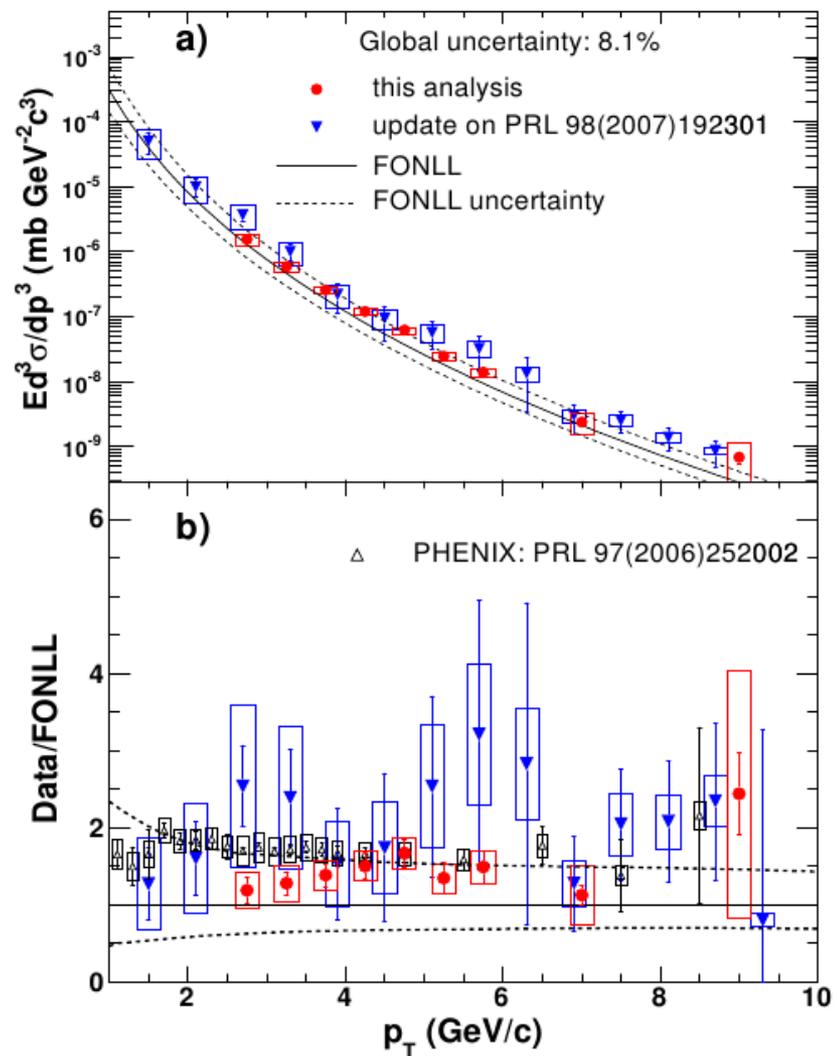


# Results

# Measurements in p+p collisions at mid-rapidity

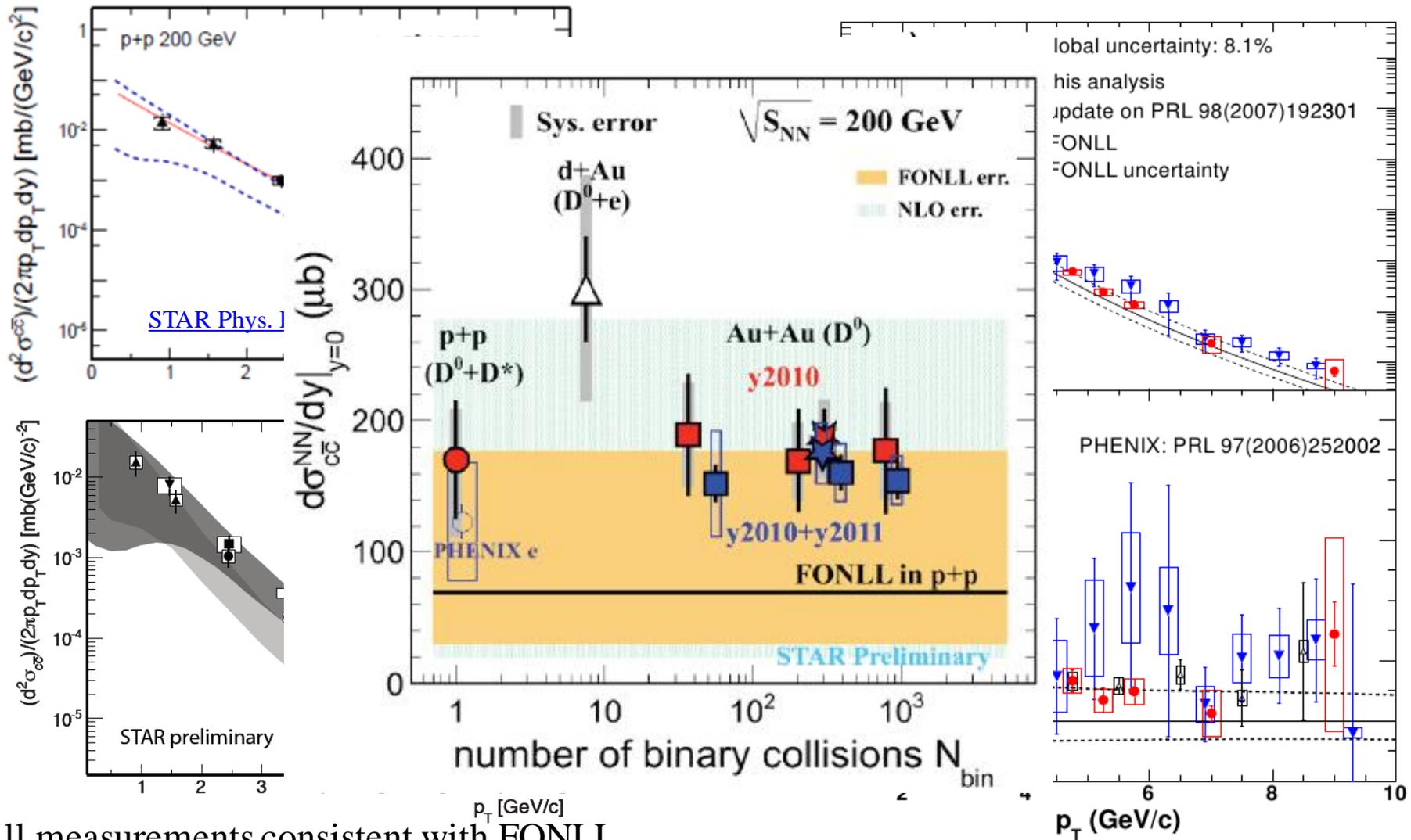


All measurements consistent with FONLL upper bound.



STAR Phys. Rev. D 83 (2011) 052006

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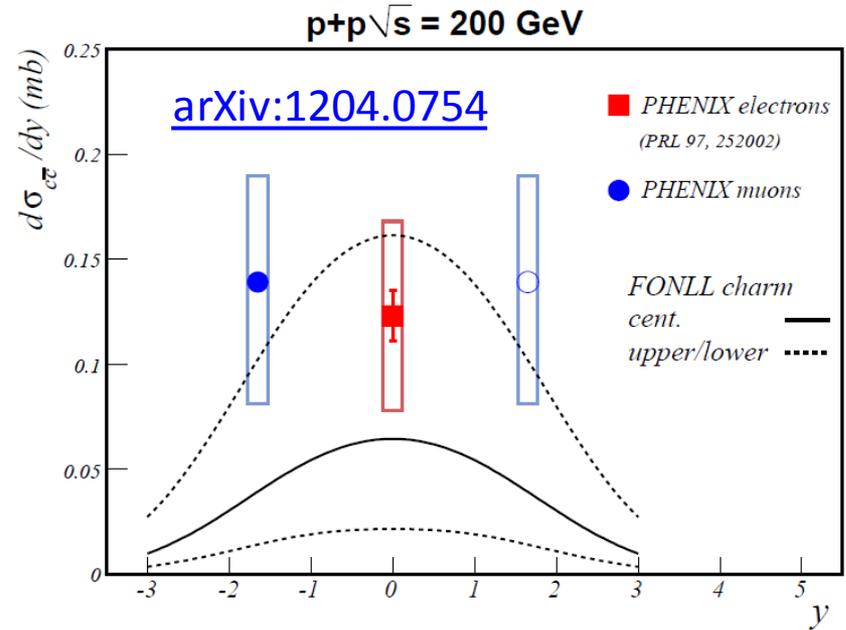
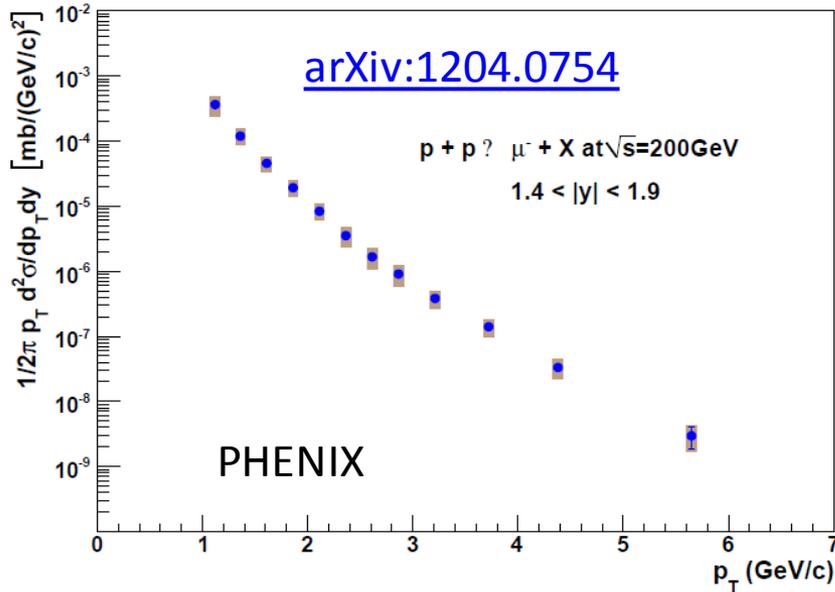


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[STAR Phys. Rev. D 83 \(2011\) 052006](https://arxiv.org/abs/1005.2006)

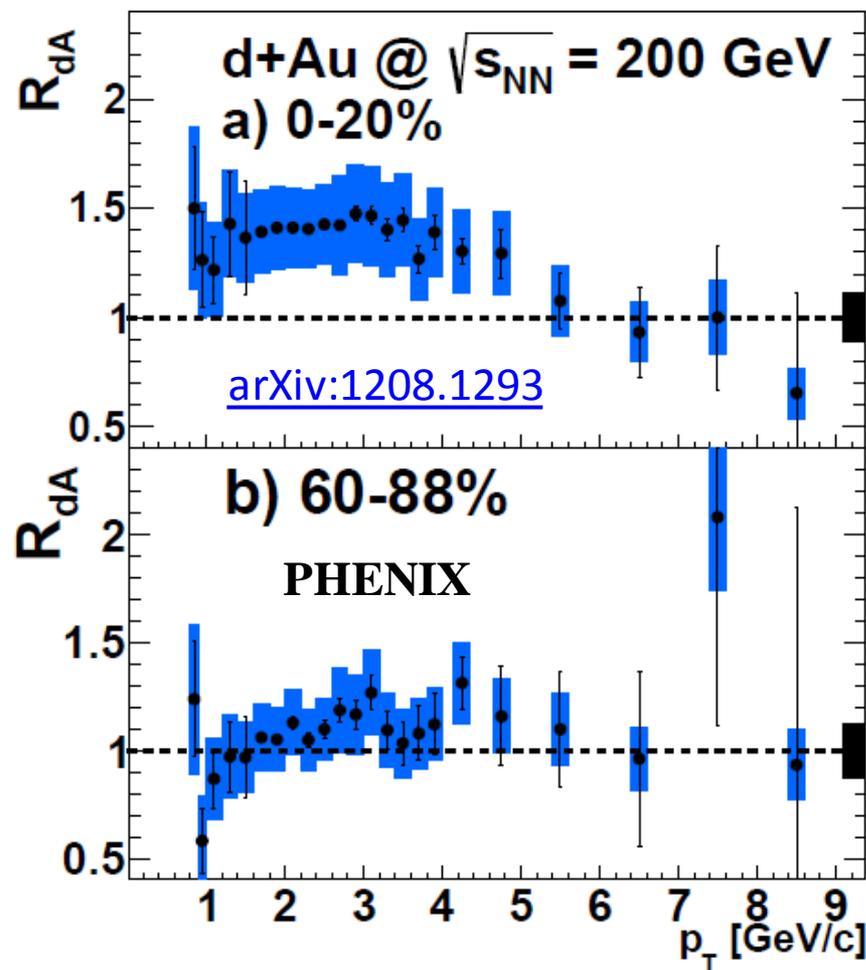
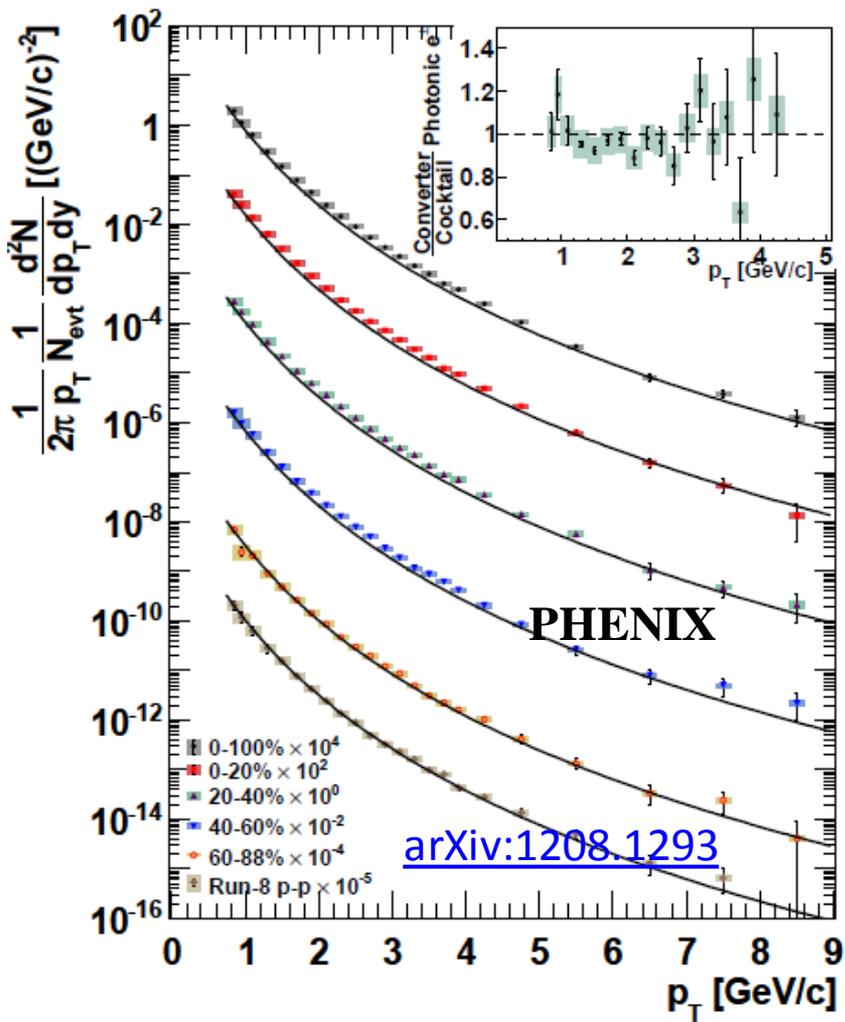
# Forward rapidity measurements in p+p collisions

## $\sqrt{s} = 200 \text{ GeV}$



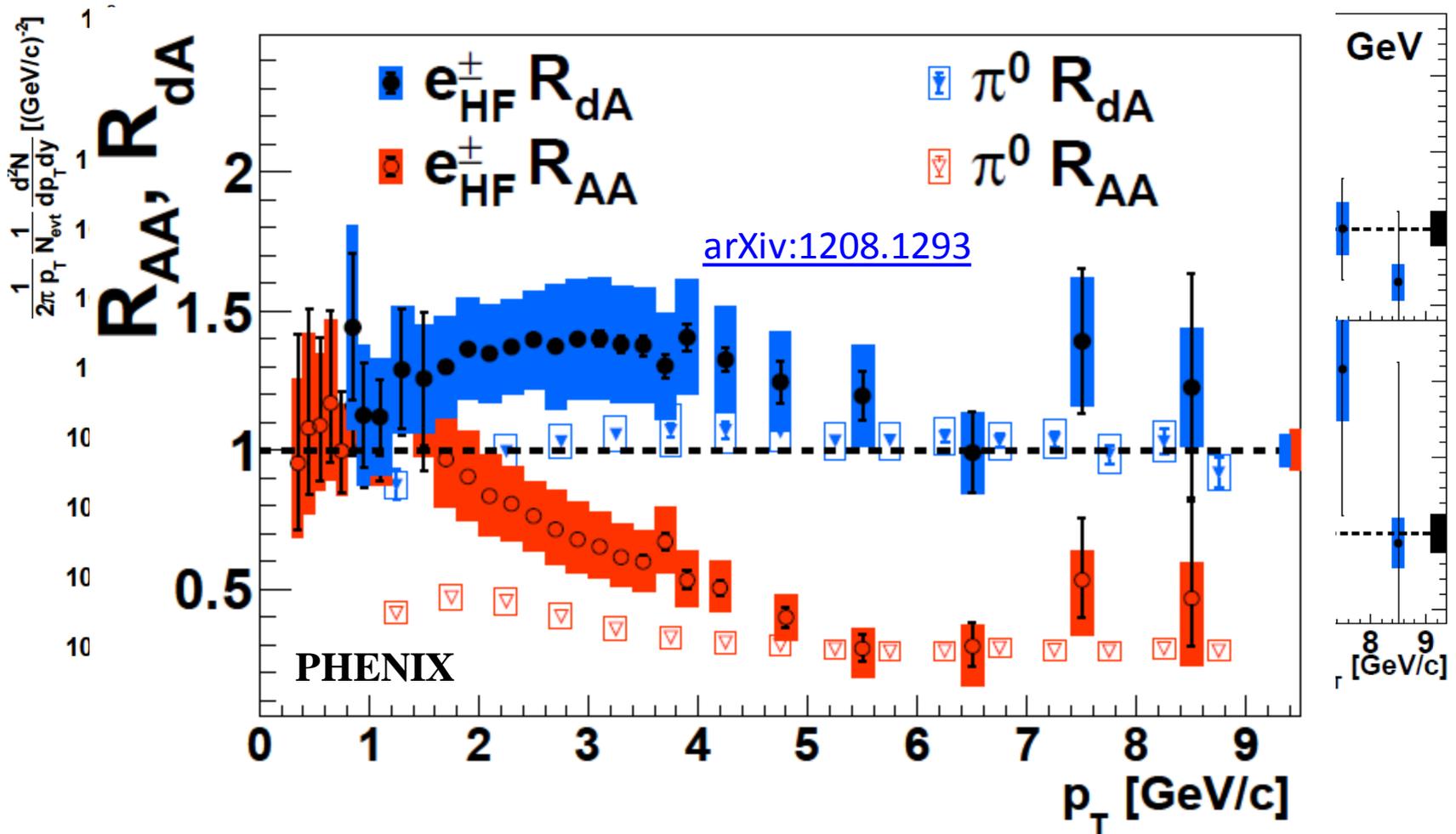
Production cross-section of negative muons from heavy-flavor decay.

# Single electrons in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV



CNM (Cronin) enhancement at intermediate transverse momentum.

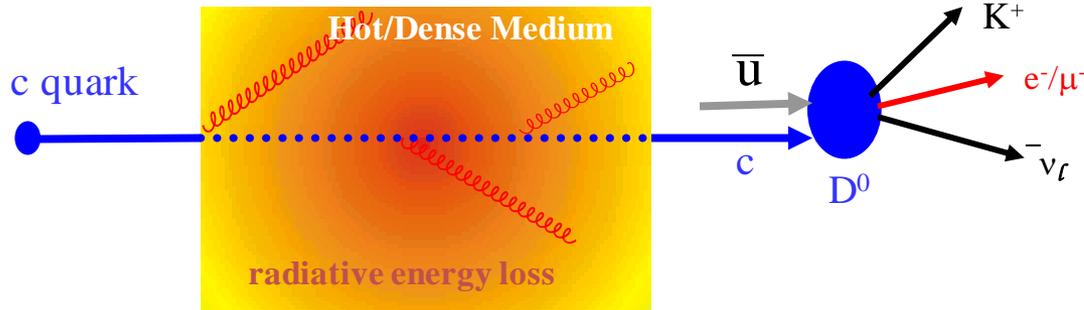
# Single electrons in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV



Mass dependent nuclear modification factor. Energy loss or CNM mass dependence?

# Heavy quark medium interaction

## pQCD

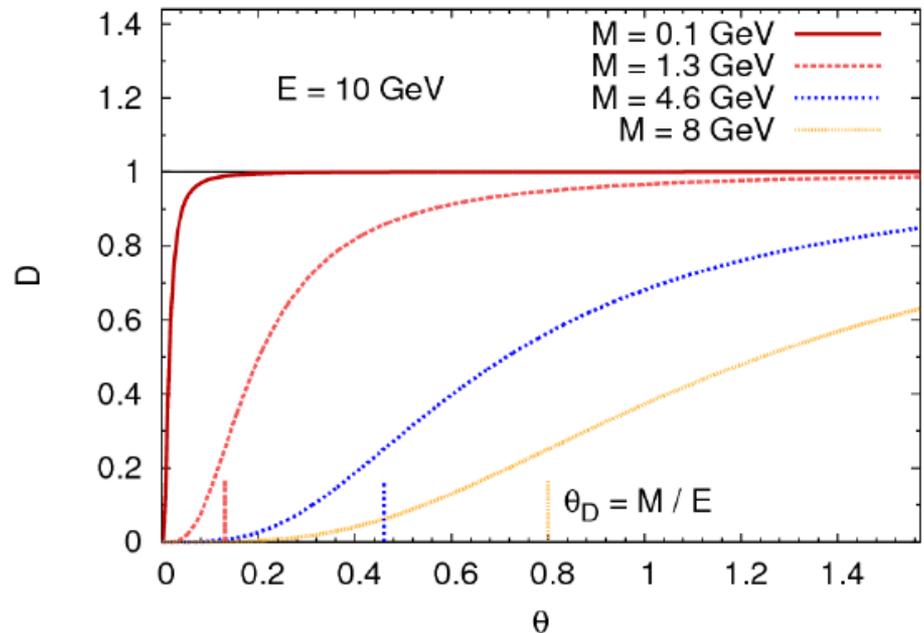


**“dead cone effect”:**  
gluon radiation  
suppressed at  $\theta < m_Q/E_Q$

Y.L. Dokshitzer and D.E. Kharzeev,  
Phys.Lett. B519 (2001)

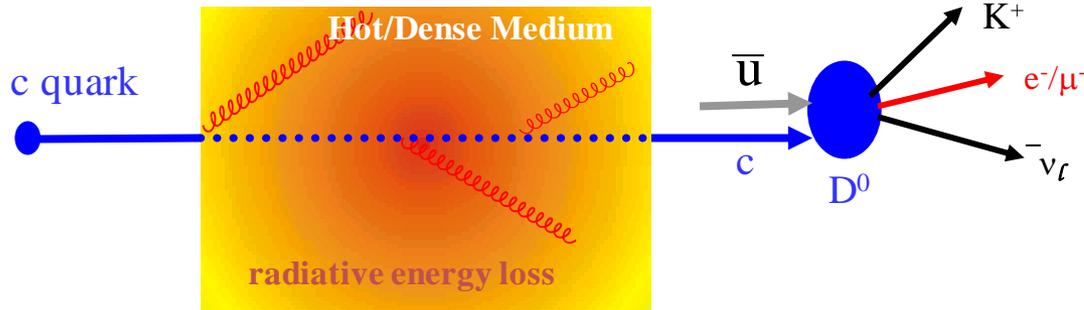
Heavy quark gluon radiation suppression factor.

Jan Uphoff, 5<sup>th</sup> International workshop on heavy quark production in heavy-ion collisions



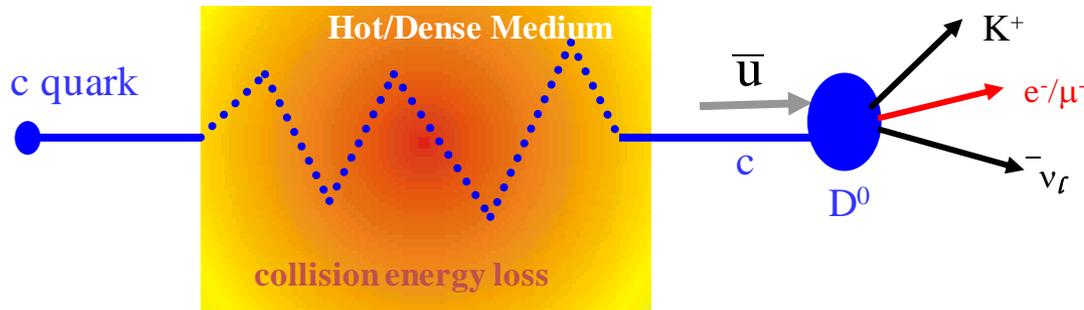
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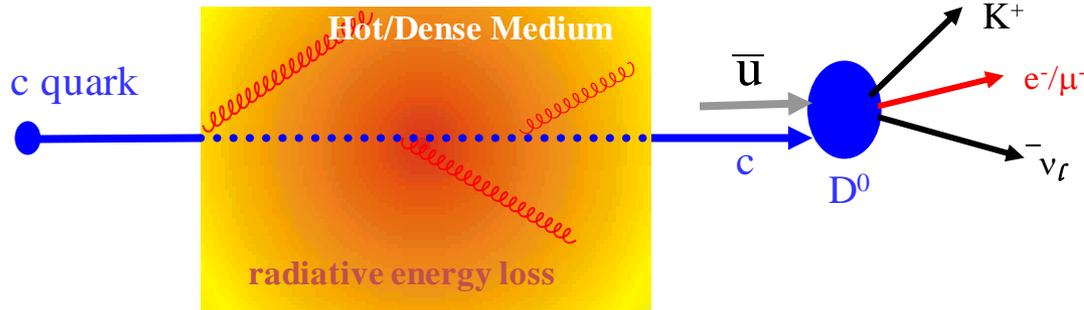
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Elastic collisions (2->2 scattering)

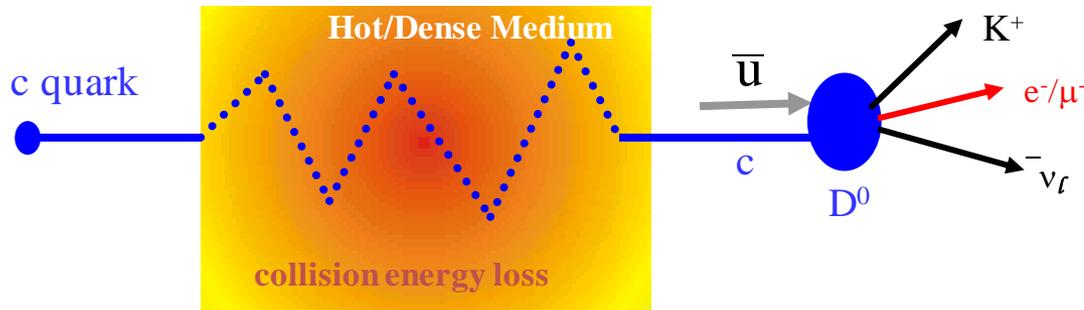
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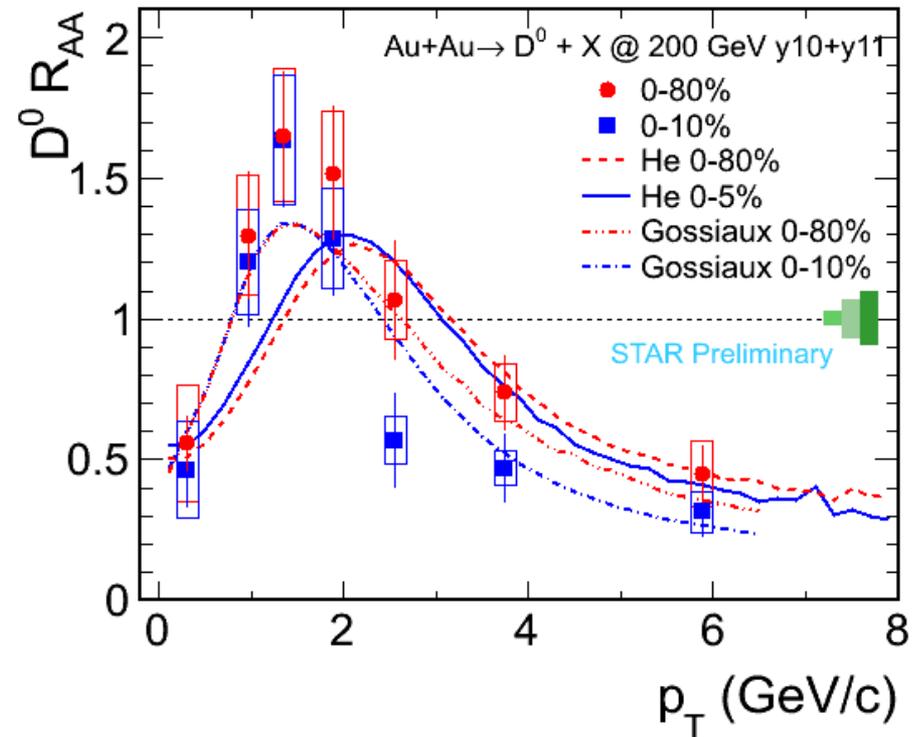
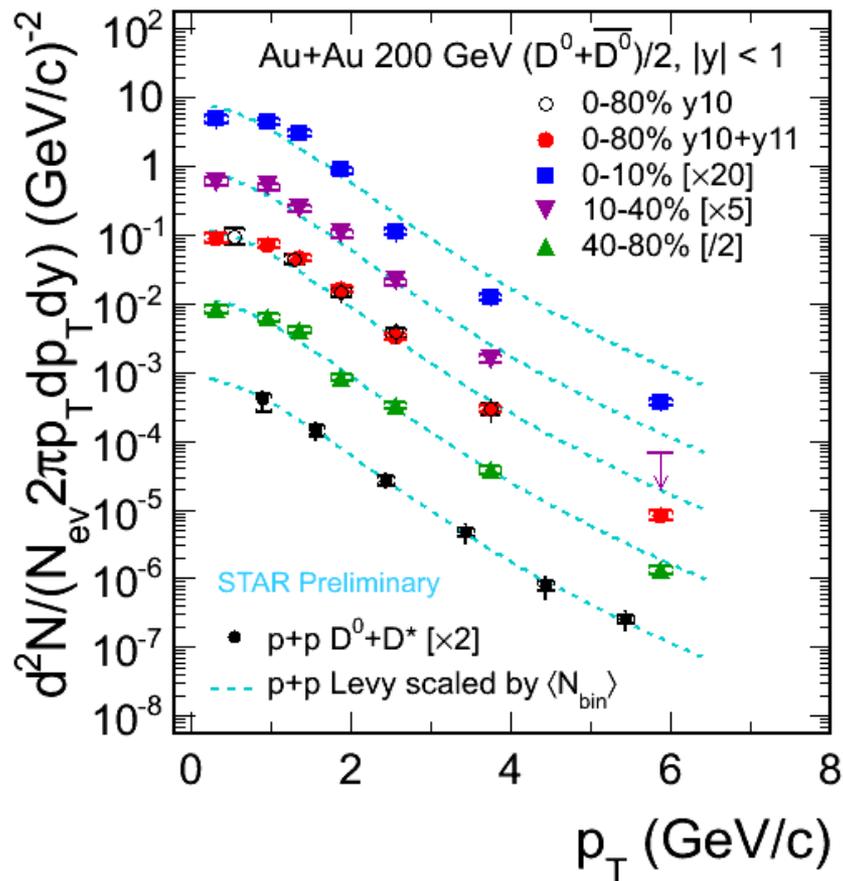
Different suppression for bottom and charm.

There is no consensus on the relative contribution of radiative and collisional energy loss. For examples see:

Peshir [hep-ph/0607299](https://arxiv.org/abs/hep-ph/0607299) Gossiaux et. al. [arXiv:1001.4166](https://arxiv.org/abs/1001.4166), Horowitz [arXiv:1108.5876](https://arxiv.org/abs/1108.5876),

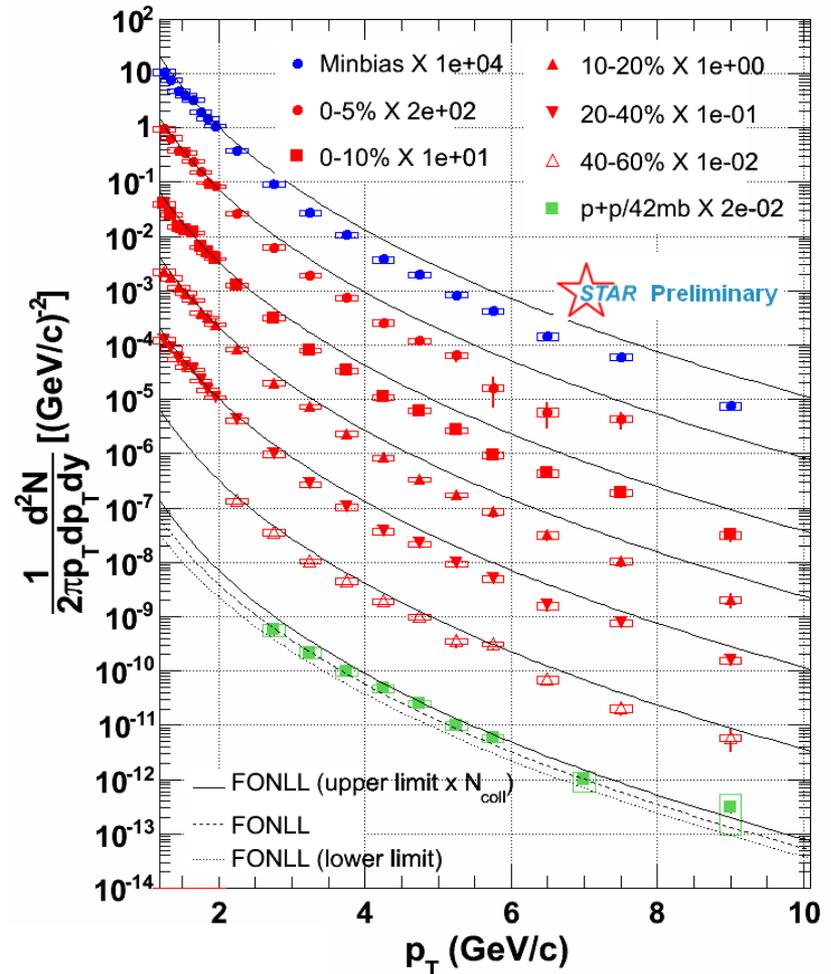
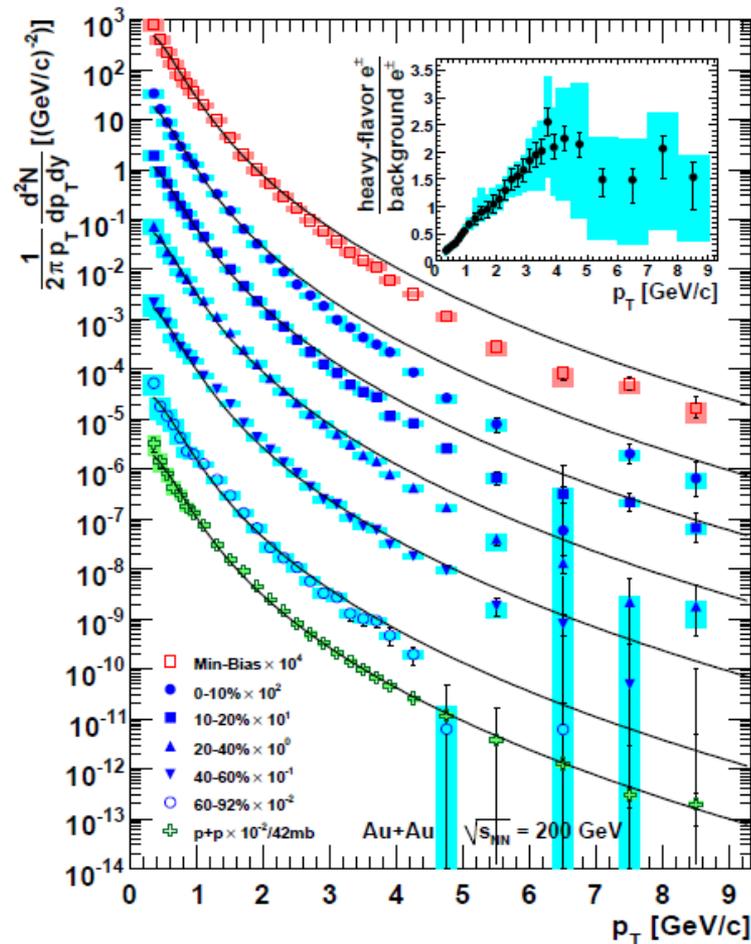
Uphoff et. al. [arXiv:1205.4945](https://arxiv.org/abs/1205.4945), Cao et. al. [arXiv:1209.5410](https://arxiv.org/abs/1209.5410), Abir et. al. [arXiv:1203.5221](https://arxiv.org/abs/1203.5221)

# Direct $D^0$ reconstruction in Au + Au at $\sqrt{s_{NN}} = 200$ GeV



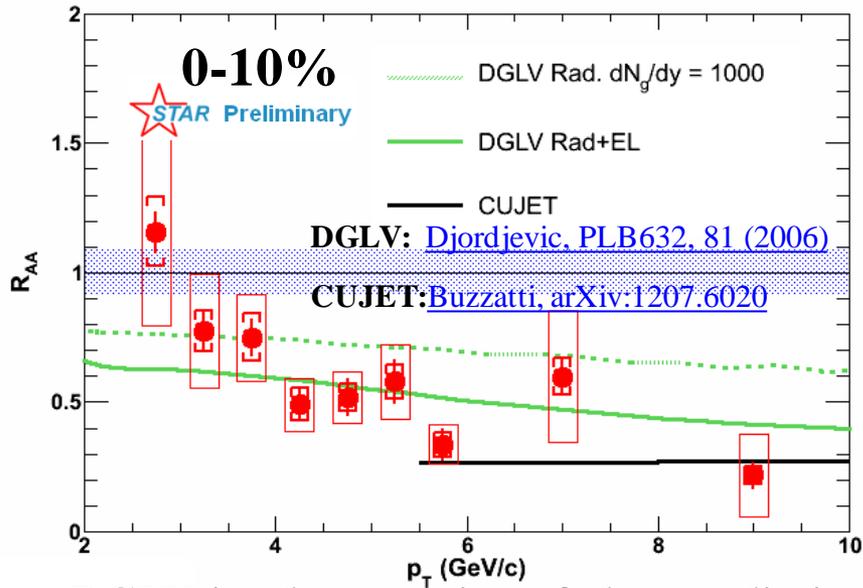
- Suppression at high  $p_T$ .
- Enhancement at  $p_T \sim 1.5$  GeV/c, radial flow of light quarks? Cronin?

# Single electrons in Au + Au at $\sqrt{s_{NN}} = 200$ GeV



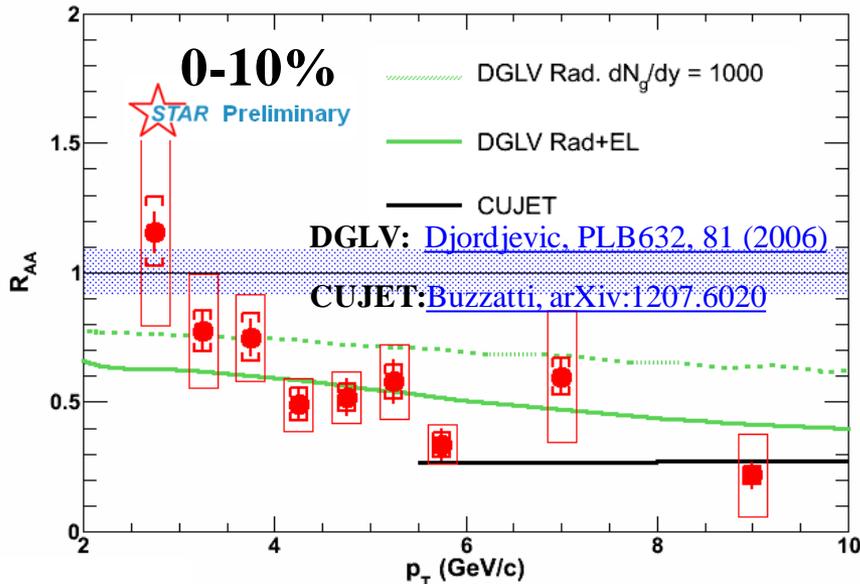
Measurements of single electrons from heavy flavor decays from PHENIX and STAR. New STAR measurement is with highly improved statistical precision.

# Single electrons $R_{AA}$ in Au + Au at $\sqrt{s_{NN}} = 200$ GeV : pQCD : radiative + collisional

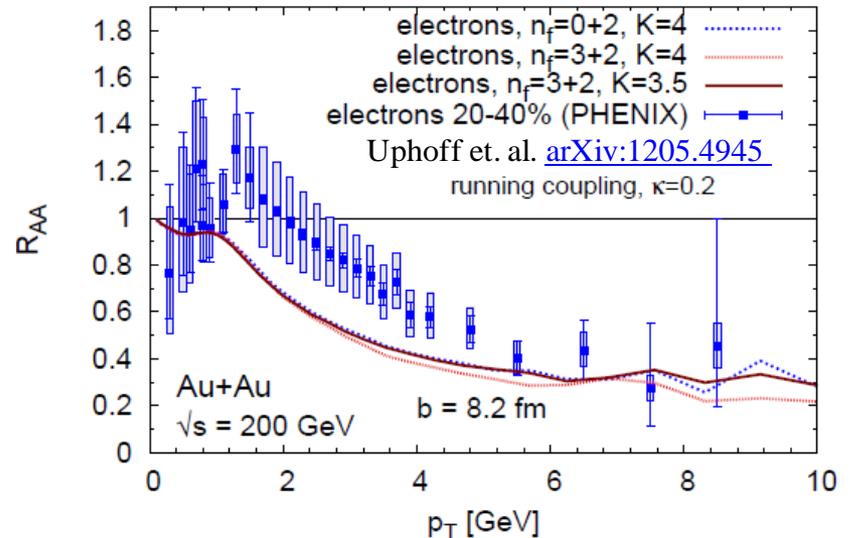
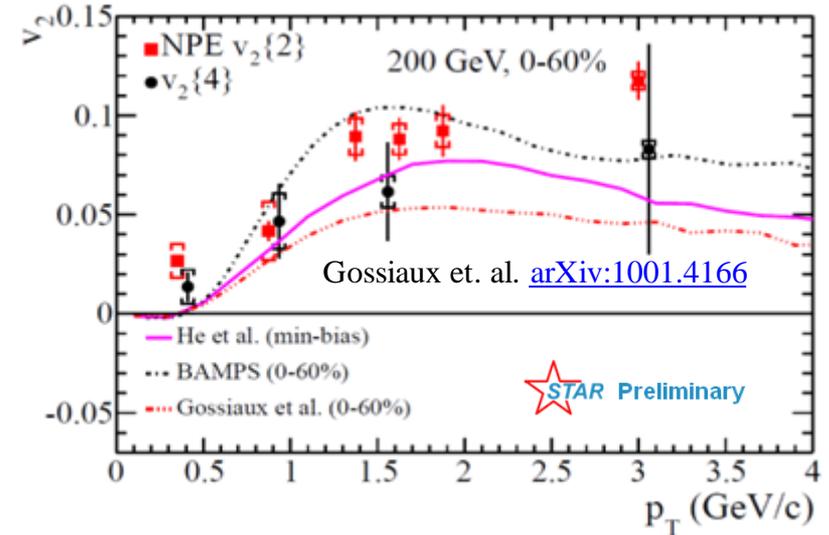


- DGLV implementation of gluon radiation under predicts the  $R_{AA}$ .

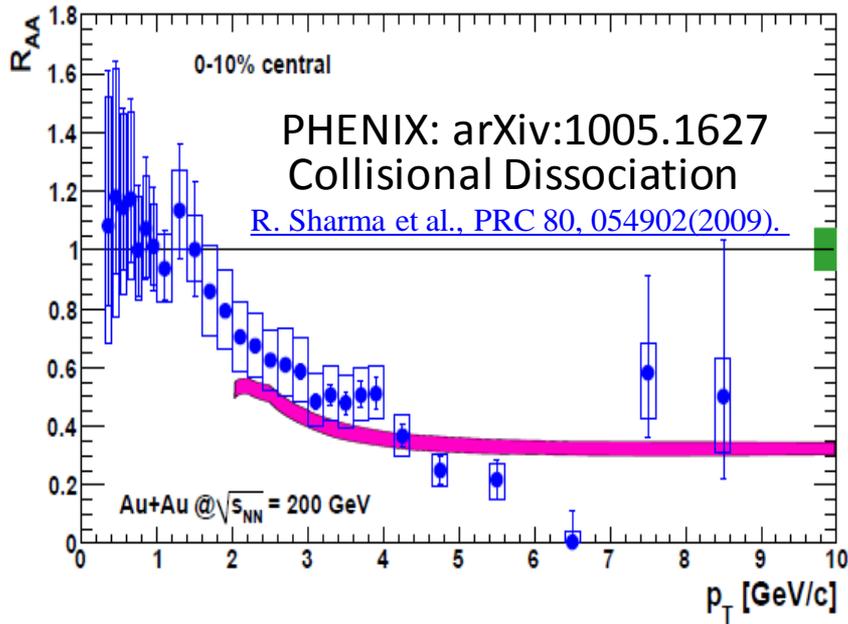
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- DGLV implementation of gluon radiation under predicts the  $R_{AA}$ .
- BAMPS, collisional + phen. factor to account for gluon radiation describes both  $R_{AA}$  and  $v_2$ .
- Gossiaux et. al. radiative + collisional describes  $R_{AA}$  and misses  $v_2$ .

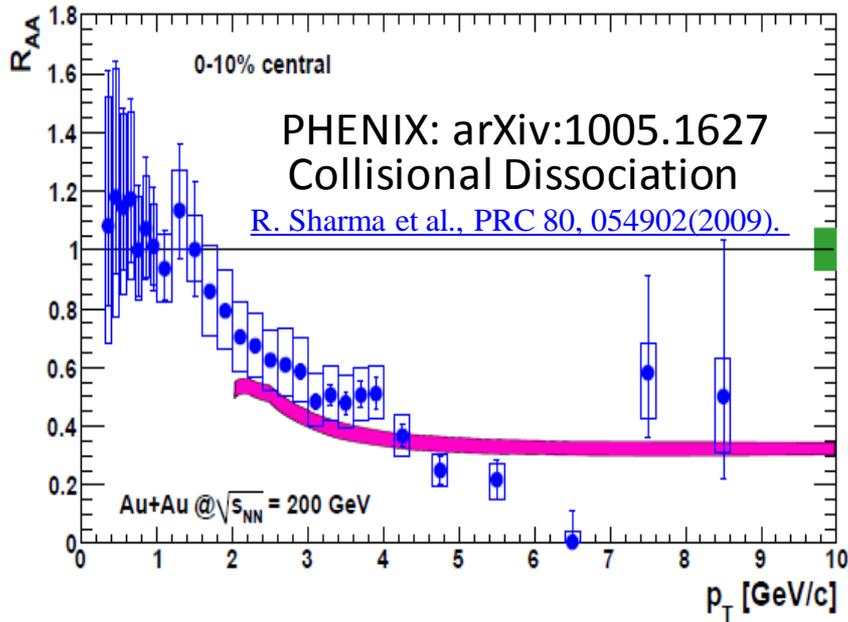


# Single electrons $R_{AA}$ in Au + Au at $\sqrt{s_{NN}} = 200$ GeV : Alternative energy loss models

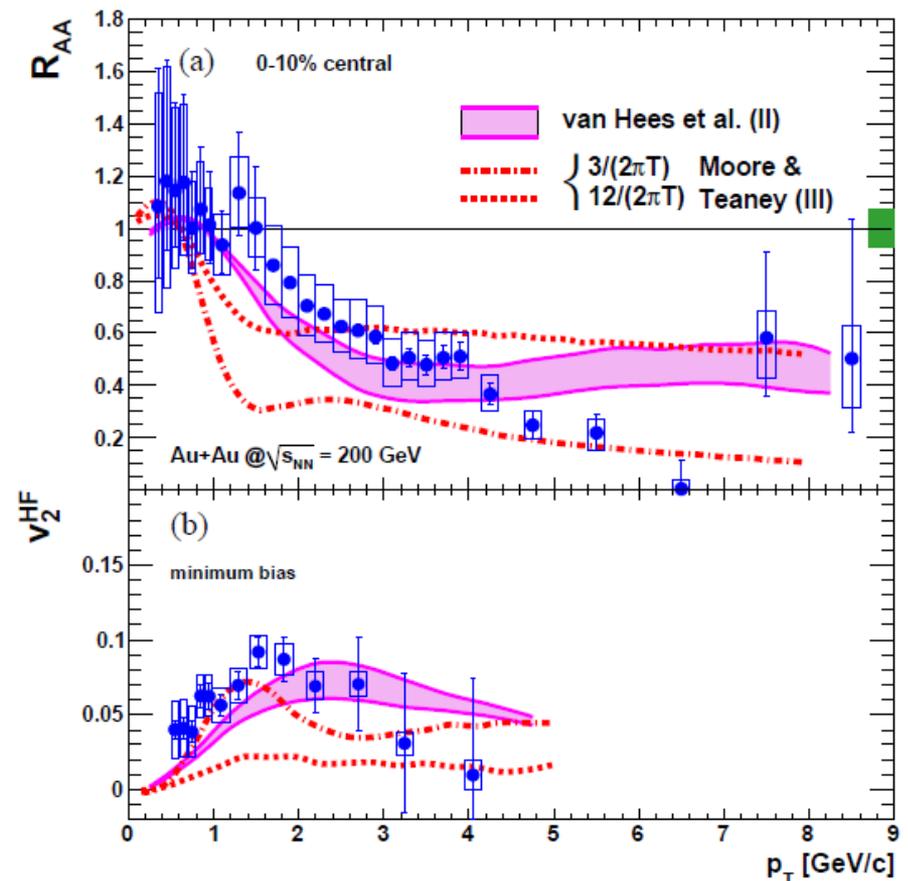


- Collisional dissociation describes  $R_{AA}$ . No  $v_2$  prediction from this model.

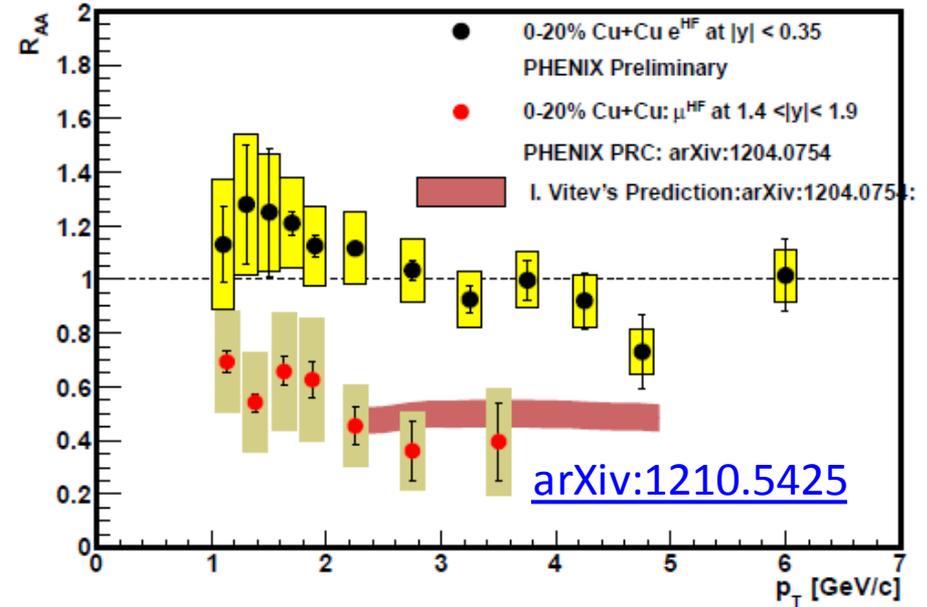
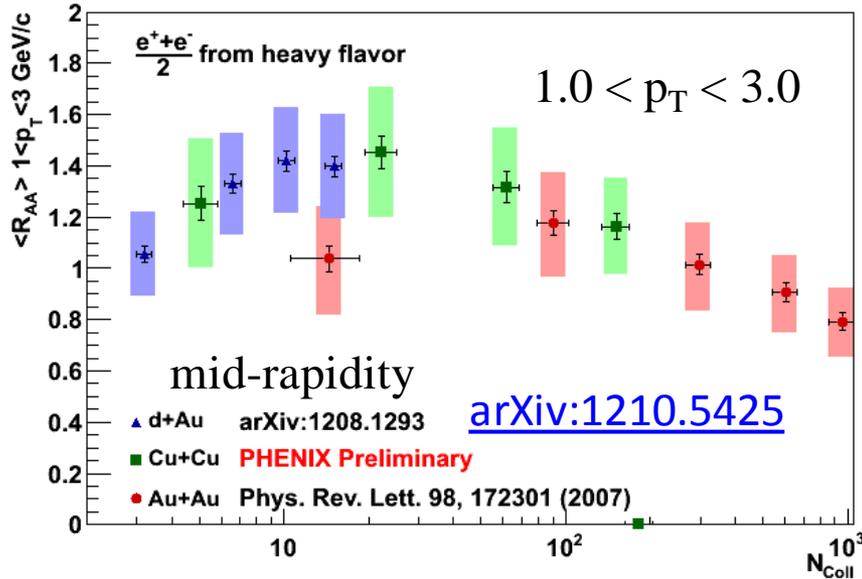
# Single electrons $R_{AA}$ in Au + Au at $\sqrt{s_{NN}} = 200$ GeV : Alternative energy loss models



- Collisional dissociation describes  $R_{AA}$ . No  $v_2$  prediction from this model.
- TAMU non-pQCD resonance scattering has a reasonable description for  $R_{AA}$  and  $v_2$ .
- Not shown: AdS/CFT based models describe  $R_{AA}$  at RHIC and over-quenches ALICE D measurement.



# Forward rapidity Cu + Cu at $\sqrt{s_{NN}} = 200$ GeV



- Similar trend in Cu+Cu and d+Au at mid-rapidity.
- Heavy-flavor production is suppressed in forward- compared to mid- rapidity.

[PHENIX Cu+Cu arXiv:1204.0754](https://arxiv.org/abs/1204.0754)

## Conclusions and outlook

- The full theoretical picture is not clear. More systematic studies of the different assumptions and calculations are still in progress.
  - Relative contribution of different pQCD processes.
  - Simultaneous prediction of  $R_{AA}$  and  $v_2$ .
  - Measurements and predictions of centrality and  $\mathbf{p}_T$  dependence.
  - Collision energy dependence.
- More experimental differential measurements needed.
  - Bottom/charm measurement separation.
  - Direct charm reconstruction  $v_2$ .

Finally, one also needs to study:

- CNM. [PHENIX, arXiv:1208.1293](#)

- Charmed baryon enhancement.

[P.Sorenson, et al. PRC74, \(2006\) 024902](#)

[Martínez-García, et al. J.Phys.G 35 \(2008\) 044023](#)

- Charmed mesons ratios  $D^0/D$ ,  $D^{+}/D$ ,  $D_s/D$  compared to production in vacuum.